PHOTOVOLTAIC (PV) TECHNOLOGY

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INTRODUCTION

Since the 1973-1974 foreign oil embargo, the US, European countries and Japan have been engaged in extensive effort to develop secure energy resources and reliable power system. They have sponsored research and development on new approaches to build a broadly based energy supply system, secure long-term energy resources, stabilize energy prices, conserve energy use and preserve the environment.

One of the most promising new energy supply options is photovoltaic which transforms solar radiation directly into electricity. It presents an opportunity to commercially tap a large, secure, inexhaustible and broadly available resource of sunlight.

PV systems have virtually no environmental impact. They are inexpensive because the fuel cost is zero and the maintenance cost is much smaller than that for most of conventional power systems.

PV systems are supposed to be very reliable since they are based on solid-state technology, which have no moving parts in the conversion process. They last a long time. At present, a typical system lasts 15-20 years and it is expected that future systems will last over 30 years.

PV systems are generally assembled by using modular units ranging from tens of watts to thousands of watts of electrical power per installation. Regardless of scale, the lead-time for design installation and start up is usually measured in months (not years as applied by a conventional system) for new installation or for additions to an existing system.

As a result of the R&D to date, PV is competitive in thousands of remote area applications worldwide. Nevertheless, these applications represent only a small fraction of the true potential of PV, a potential that can be obtainable by further reducing the costs and improving the performance of PV modules and systems. Improvement and optimization of manufacturing processes are also considered necessary in order to disseminate broader use of PV, especially in the utility grid application.

PV PRINCIPLE

The basic power element of a PV system is the solar cell. Typical solar cells are made of crystalline silicon, a material of the semiconductor revolution. The photovoltaic effect in silicon and other semiconductor materials arises from the internal electronic structure and the electric fields that can be introduced. One way is to use two or more thin layers of two different semiconductor materials. Another way is to introduce different dopant atoms (atoms that have one more or one less valence electron than the host material) into two different thin layers of a structure using the same semiconductor material. A junction formed between two of these layers creates an internal voltage. Sunlight striking the solar cell liberates electrical charged carriers (Holes and Electron) within the cell. The electric charges are separated by the internal (Junction) voltage to produce an electric current.

Metal contact grids (lines) on the top and bottom surfaces of the cell enable the current to flow through an external circuit to produce electrical power; electric power is the product of voltage and current resulting in electricity available directly from sunlight.

A typical crystalline silicon cell produces a little more than one watt of power. More power can be produced by interconnecting several solar cells and encapsulating them in a single package called a PV module. Modules may in turn be grouped together and interconnected to form arrays. The DC power from PV array can be used to power DC load or passed to a power conditioning subsystem (PCS) that converts DC to power AC load. In this simple manner, one can combine cells, modules, arrays and PCS to design PV systems that will provide any desired power output from few watts to many megawatts.

TECHNOLOGY DEVELOPMENT

During the relatively short history of PV (since 1954), industry has used the growing technology to phase PV products into commercial use. Industry decisions have depended upon evaluation of the readiness of technology and its near-term potential and market projections for anticipated products.

Such a decision led to the earliest commercial PV products using silicon cells for space power need, and later for small, remote terrestrial power system. The combined R&D efforts of industry, the research community and the US National PV Program have rapidly expanded PV technology, leading to many new results. A number of new ideas, materials and system approaches have continually and rapidly increased. There will be growing choices of technologies for industry to be introduced because substantial technical progress is improving on existing PV technologies and pushing new one towards maturity. Crystalline silicon technology, for example, is still progressing and must be considered as one of the major choices for further implementation by industry. The same is true for poly crystalline silicon and for ribbon silicon. Thin-film technologies show considerable progress and potential and must be considered as major competitors. These include amorphous silicon and its alloys, copper indium de selenide and its alloys, cadmium telluride and its alloys and thin-film single-crystal gallium arsenide. Crystalline silicon technology continues to be an important area of R&D in the US DOE program. Recent achievements in improving cell and module efficiency indicate that silicon will continue to have potential as a cost-effective technology. However, even though industry has used the technology base to reduce module costs to less than $ 4-5 per watt, the cost of silicon materials and processing cells made from crystal wafers remains obstacles to achieving cost-effective crystalline silicon systems for utility applications. To overcome these obstacles, R&D program has been continued on the fundamental of crystalline silicon and devices. Silicon sheet, so called because sheets of silicon are grown directly from molten silicon, offers a potential solution to the high costs of materials and processing. For industry to achieve long-term commercial success with this technology, however, it must improve the sheet growth rate while maintaining high cell performance. Based on progress it made in these areas, industry should be able to introduce significant quantities of silicon-sheet PV systems into power markets within a few years.

Amorphous silicon and poly crystalline thin-film cells, which are about one hundred times thinner than crystalline silicon cells, use very little semiconductor material and offer a long-term potential for significantly lower costs. Further, entire thin-film modules, rather than individual cells, can be fabricated in an automated production process. As a result of advances in R&D programs, the cost of PV generated electricity has decreased from an estimated $ 1.50 per kilowatt-hour in 1980 to around 15 cents per kilowatt-hour today. U.S. research, which leads the world in gaining new understanding of the mechanism that limits the performance of thin-film device, is being undertaken to bring the cost of PV electricity down to the goal of 6 cents per kilowatt-hour. This work has been creating a growing number of options to achieve technologies that should not only be competitive for near-term but also for long-term power needs.

UTILITY PERSPECTIVES ON PV

As the technology advances, some electricity utilities are developing a growing confidence in PV power. The diversity among electricity utilities and uncertainties over future capacity implies that PV can become a viable option to different utilities within different time frames. Today, more than 70 utilities around the US are actively involved with PV. Some are even pursuing research on cells, modules and hardware; others are evaluating components, system and large-scale plant designs. Some are buying large amounts of PV power through third-party arrangements. Importantly, some are making significant investments by installing PV system. One is installing a PV MANUFACTURING FACILITY. The following perspectives from utilities indicate their growing commitment to PV:

Electric Power Research Institute (EPRI)

"In the end, the solution of our energy quandary depends on the nation's readiness to take advantage of the full range of its energy options. The issue is not a choice of conservation or coal or nuclear or renewable resources: rather it is our willingness to use conservation and coal and nuclear and renewable resources. We do not enjoy the luxury of selecting from these alternatives; we must utilize all of them."

Arizona Public Service 1984 Annual Report

"Our research group will focus its efforts on analyzing the feasibility of renewable energy sources. We have already positioned ourselves as a leader in solar technology. During 1984, we continued to produce energy from the 225 kW sky harbor solar PV facility, and we met approximately 40% of the energy needs of an experimental PV home in southern Arizona."

Pacific Gas and Electric Company 1985 Annual Report

"Among the alternative energy projects contributing to PG&E energy mix is the nation's largest solar PV plant in central California. The plant produces electricity directly from sunlight. The company is evaluating the performance of the project to help design more advanced PV plants. Now and for the near future, solar PV are too expensive to be commercially attractive. When the market does develop, however, PG&E intends to be ready to serve it."

The Southern Company 1985 Annual Report

"The Southern Electric System (the parent firm of four electricity utilities: Alabama Power, Georgia, Gulf Power, and Mississippi Power) is involved in advanced research to test promising energy and environmental technologies. PV cells, which convert sunlight directly into electricity, are moving closer to becoming source of electric power. The Southern Electric System is investing $6.1 million in a high-technology plant that will manufacture PV cells made of the layers of amorphous silicon. Alabama is managing the system's participation in the project."

New England Electric System

"Energy costs are going up; demand is going up; PV costs are coming down. Somewhere in the future there is a point where the economics of PV will be attractive. Logically, PV will have to be a source of utility generation."

Cost Decreases for PV Pioneer Installations

Year	System Cost (turn-key)	SMUD Program Cost	Total Installed Cost	Energy Cost 30 yr. c/kWh
1993	$ 7.70	$ 1.08	$ 8.78	23c
1994	$ 6.23	$ 0.90	$ 7.13	20c
1995	$ 5.98	$ 0.89	$ 6.87	19c
1996	$ 5.36	$ 0.85	$ 6.21	17c
1997	$ 4.75	$ 0.59	$ 5.34	16c
1998	$ 4.25	$ 0.82	$ 5.07	16c
1999	$ 3.75	$ 0.75	$ 4.50	14c
2000*	$ 3.25	$ 0.65	$ 3.90	12c
2001*	$ 2.80	$ 0.62	$ 3.42	11c
2002*	$ 2.69	$ 0.49	$ 3.18	10c
2003*	$ 2.59	$ 0.39	$ 2.98	9c

All costs in $ per kW (PTC; A/C). *Committed contract price.
Energy cost levelized over 30 years at District cost of money or 1st mortgage rate.
Source: SMUD

Table 1 PV world market (MW)

	1990	1993	1996	1997	1998	1999
Consumer products	16	18	22	26	30	35
US off-grid residential	3	5	8	9	10	13
World off-grid rural	6	8	15	19	24	31
Communications and signal	14	16	23	28	31	35
PV/diesel, commercial	7	10	12	16	20	25
Grid-connected residential, commercial	1	2	7	27	36	60
Central > 100 kW	1	2	2	2	2	2
Total (MW/year)	**48**	**61**	**89**	**127**	**153**	**201**

(*PV Energy System*, March 2000)

Table 2 World PV 1999 and market forecast

	1999	2000	2005	2010
Consumer products	35	40	70	100
US off-grid residential	13	15	30	50
World off-grid rural	31	35	80	200
Communications and signal	35	40	60	200
PV/diesel, commercial	25	10	60	150
Grid-connected residential, commercial	60	110	300	800
Central > 100 kW	2	5	50	200
Profitable module (factory price $/Wp)	$3.75	$3.50	$2.00	$1.50
Profitable installed cost $/Wp	$8.00-12.00	$7.00-12.00	$4.00-8.00	$3.00-6.00
Total (MWp/year)	**201**	**255**	**650**	**1700**

(*PV Energy System*, June 2000)

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ANNEX

Photovoltaic history has been replete with setting and meeting challenges and with phasing mature technologies into the marketplace. Photovoltaic has before it the challenge to make it competitive with some of the nation's major energy sources and to phase the emerging technologies into the utility market and into the nation's energy mainstream.

In a typical cell made of crystalline silicon, sunlight frees electrical charge carriers (electrons and holes) that are separated at the junction. This creates an internal voltage that drives current through an external circuit.

Source: US DOE